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# A STUDY OF WATER ICE FORMATION AND MELTING PROCESSES ON VERTICAL COOLED PIPES

*The use of cold accumulators based on the principle of water ice formation on the cooled surfaces during off-peak periods and water ice melting during on-peak periods is an effective method of electricity bills reduction. Within comparatively short periods of on-peak demand a noticeable amount of thermal energy related to ice melting is to be released, it becomes clear that not only sizing of ice accumulators based on balance calculations is actual, but also the determination of time periods of ice accumulation becomes critical. This work presents an experimental unit for obtaining data on the ice formation on the vertical cooled pipes and later on to continuously register data on the ice thickness diminishing at the regimes of ice melting when cooling of pipe stops. The data for ice formation and melting for some regimes have been presented and analyzed. The data form the base for deriving semi-empirical correlations allowing to determine time intervals necessary to generate of water ice layers of given thickness.*

***Keywords:*** *Ice; Differential equation; Ice formation rate; Water Ice; Melting; Experimental unit.*

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## I. INTRODUCTION

Electrical motors of refrigeration compressors are the biggest energy consumers at food industry. Dairy industry is characterized by a significant refrigeration capacity for water cooling and extremely uneven energy consumption charts. Ice water is being used in raw milk pasteurization which usually happens right after milk reception at dairy plant. This peak cooling load usually is accompanied by a serious growth of cooling load due to the increased sensitive head influx through the building envelope, increased input of product. Unfortunately, the factory on-peak electricity consumption coincides with the grid on-peak energy demand, and thus, energy consumed during peak periods has to be paid at the highest tariff.

Modern office building and malls are equipped with powerful air-conditioning plants (Installed power up to 12-20 MW). Growth in energy consumption takes place at mid days and coincides with mild peaks or on-peak period of grid power demand.

A detailed analysis of energy shifts is given in [1,2,3].

In articles [4,5] a differential equation was derived which allows to determine duration of ice build-up to the given ice layer thickness. But it has the values of heat transfer coefficients from water to the growing ice and to the evaporating refrigerant. The both can not be determined with the necessary level of accuracy. Thus a direct experimentation is necessary.

## II. EXPERIMENTAL RIG

A lay-out of the experimental rig designed and constructed for the determination of ice formation time rate is shown in Figure 1.

The rig consists of three similar blocks (Test sections 1-3). The main part of a section is a test copper tube 290 mm height, 10 mm outer diameter, 1 mm wall thickness. Each tube is mounted inside of water jacket of 180 mm diameter.

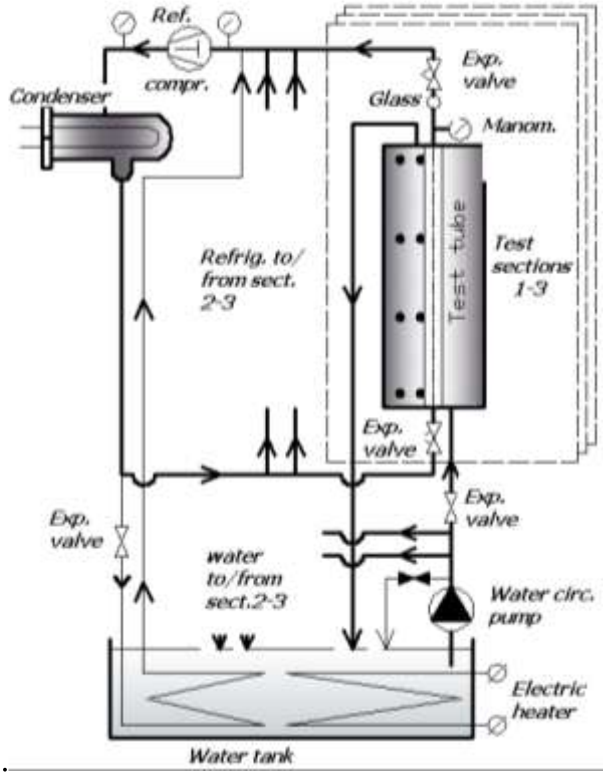
A water circulation contour consists of a pump, water piping, water tank, measurement and control systems including regulation and stop valves.

Circulating water was fed in parallel and supplied from the bottom of the jackets and removed from the upper part, so that an upward flow of water inside all jackets took place. The flow rate of water was controlled by a rotameter, adjusted and kept constant during every experimental run by precision needle valves, and precisely measured by the volumetric method. The water flow rate could be maintained individually for each test unit.

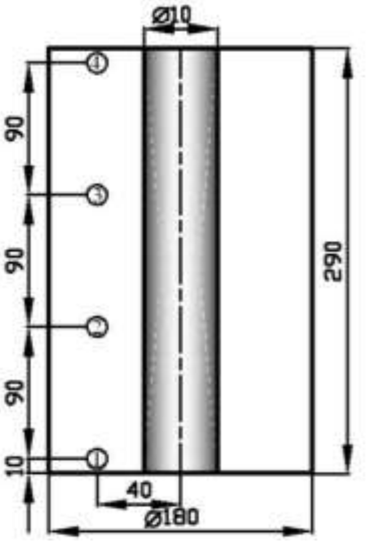
A given temperature at the entry to the jackets has been maintained by switching on / off of a cooling coil or electric heater in the water tank.

The test tubes were hooked up to the refrigeration (R12 and R22) contour in parallel on the refrigerant.

Although the refrigerants named above are forbidden or phased out for usage in the refrigeration and air conditioning installation in EU, their use still allowed in the laboratory and experimental units where possible leakage is negligibly small (see. EU Reg. № 1005/2009) [6]. Surely, the refrigerants used in now way are intended to be used in any equipment, but rather the experimental data obtained are intended to serve a reference for a wider generalization and aimed at the derivation of an empirical correlation allowing to calculate the duration of ice growth valid for the range of refrigerants with sufficiently different thermo physical properties. Further on a set of similar experiments with R-134 and R-404 will be carried out and the data will allow to extend the range of refrigerant's physical properties variation.



a)



b)

***Figure 1** – Experimental rig:*
*a – lay out, b- cross sections of thermocouples' location*

The refrigeration unit has been equipped with all necessary systems allowing control, measurements and regulation of the evaporation pressure (evaporation temperature) inside each test tube and condensation pressure in the condenser.

A set of thermocouples installed in four equally spaced cross sections along the tube, see Fig. 1b allowed measurements of temperature of water at a distance 40 mm from the tube surface and tube outer surface temperature at the same cross section.

Time rate of ice layer thickness formed during the experiments was measured by means visual technique. Photographs of the test sections of pipes covered with ice were taken from the front of the transparent water jackets. Immediately before the experiments, an adjustment session had been carried out including testing of different lighting techniques and light sources, and calibration procedures which aimed at the determination of the best measurement arrangements.

Photographs were taken with a digital camera Canon 350 D 8.2 MP and simultaneously with a web camera HP HD-4110 (13 MP). Web cameras attached to each test section operated by the Active WebCam software which allowed taking pictures of the test pipes at any chosen frequency and storing individual video files for every section. Along with taking pictures with the web cameras the individual pictures were taken with the frequency 1 picture per 30 second with a Canon 350 D camera. Synchronization of the pictures taken by the Canon photo camera on the time scale of the web camera has been made by shooting a laser pointer beam on the test pipe simultaneously with taking picture with the Canon camera along with the continuous filming the process with the web camera (Figure 2). The picture made by the Canon camera with the red point collated with the individual shot of the web camera film with the same red point.

***Figure 2** – Synchronization of individual cadres*

The measurements of iced pipe diameters have been performed by a set of on screen measurements software (ScreenRuler, PixRuler, Acad) (Figure 3). All of them gave the results with the deviation of 0.2...0.4 mm.

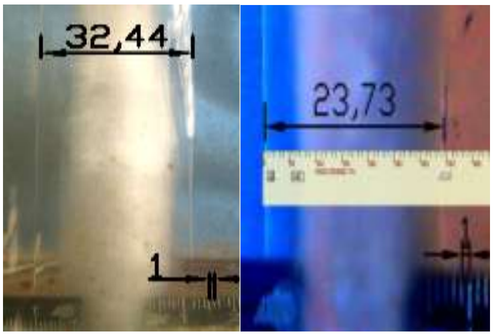


***Figure 3** – Ice layer thickness measurements*

## III. EXPERIMENTAL RESULTS

All experiments were carried out at a fixed water flow rate which corresponds to Re=445÷635 and water inlet temperatures +1.5 ºC, +4÷5 ºC, +7÷8 ºC, and +10 ºC.

Within a set of experiments on ice build up the evaporation temperature (pressure) was kept constant at the levels -5 ºC, -9÷10 ºC, -15÷16 ºC, -20 ºC and -25 ºC, whereas within the experimentation on ice thawing the cooling of heat transfer surface stopped. The data obtained within the sets of experiments allowed representing the "history" of temperature changes at characteristic points of the refrigeration contour (Figures 4 and 5). As a starting point on the time axis the time of the ice appearance on the cooled pipe has been taken.

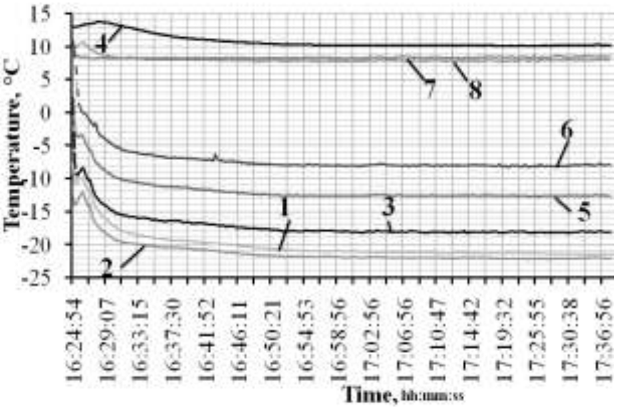


***Figure 4*** *– Temperature change within the experiment duration at the characteristic points at* $t_0$*=-10°C,* $t_w$*=+1,5°C:*
*1÷6 –refrigerant temperature at characteristic points;*
*7÷8 – water temperature at the condenser.*

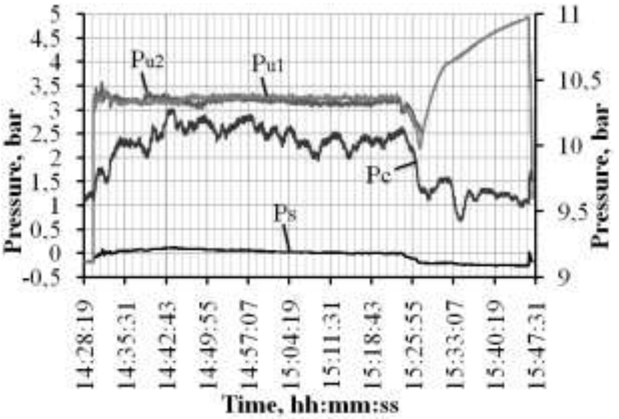


***Figure 5*** *– Pressure change within the experiment duration at the characteristic points at* $t_0$*=-5,1C,* $t_w$*=+1,7°C:* $P_c$ *– condensation pressure;* $P_s$ *– suction pressure;* $P_{u1}$ *and*$P_{u2}$ *– evaporation pressure in sect.1 and 2.*

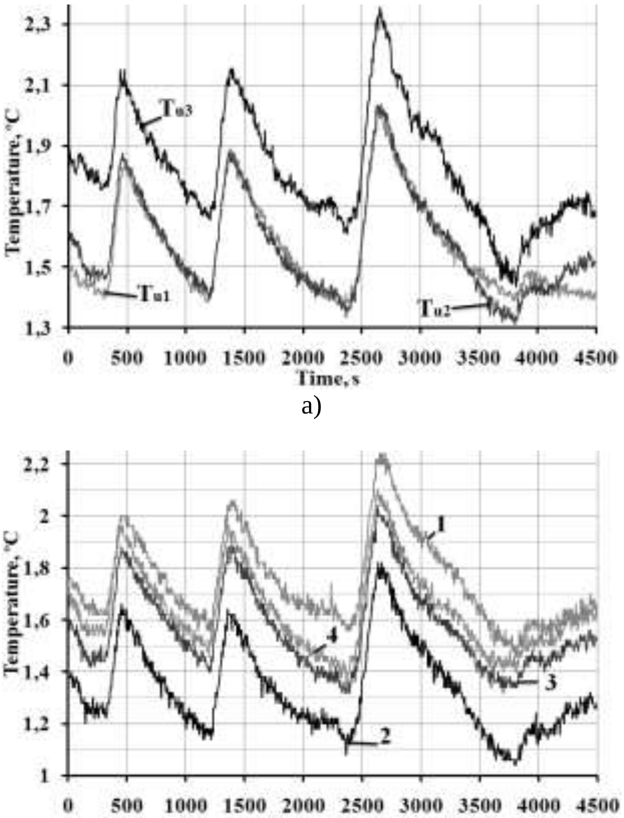
Data at figures 4 and 5 prove that the process within the refrigeration contour may be considered as stationary one, despite the fact that the external heat transfer was not due to the continuous ice growth on the outside of the pipe.

As it follows from the data Figure 4, the temperature on the suction side have reached its stationary value in 240 sec (6 min) and further on its change would not exceed 3 ºC. At the same time, the evaporation pressure in the experimental sections (Figure 5) reaches the set value practically immediately. The set value of the evaporation pressure has been carried out within the time of 60…240 sec for the experiments with the evaporation temperature -5 ºC and within 60 sec for all other series.

Since the duration of the stabilizing period would not exceed 12% of the whole experiment's duration and as a rule coincides with initial (the most intense) ice formation, a slight variation of pressure within this period may well be neglected.

The plots of the water temperature change in the experimental units (Figure 6a) show that temperature difference does not exceed 0,3 ºC and is insignificant. This negligible difference can be explained either by a systematic error of measurements or by some unaccounted heat input.

At the same time, the deviation of water temperature on the height of the experimental sections does not exceed 0,5 ºC and was kept within the limits +- 0,5 ºC.



a)

b)

***Figure 6*** *– Water temperature change in experimental sections at* $t_0$*=-5,1°C,* $t_w$*=+1,7°C: a - mean water temperature in sections, b - water temperature at height of section,* $T_{u1} \div T_{u3}$ *– temperature in sections, 1÷3 respectively;1÷4 – temperature at height, beginning from the bottom*

It is clearly seen for the data at Figure 6 that within a whole experiment duration the water temperature varied insignificantly, which allows to easily determine the value of a mean water temperature within the experiment duration and use it for further analysis.

Visual observations show that ice formed at different temperature differences (water-evaporating refrigerant) looks different. At bigger temperature difference especially at higher water temperatures, ice formed is dim, non-transparent with rough porous surface, whereas the ice formed at moderate temperature difference and water temperature 1.5...3 ºC is dense, completely transparent, although the ice layer thickness reaches 30 mm and more. The surface of ice is glassy. The later is shown in Figure 3. The data obtained with the refrigerants R12 and R22 demonstrate in general the same trends of reaching an asymptotic value of ice thickness for a given temperature head but for each respective series for the two refrigerants there is a significant difference in maximum asymptotic ice thicknesses at the comparable process parameters. Since the external heat transfer parameters are kept significantly the same (which determines full equivalence in the external heat transfer coefficients), the marked difference may be explained only by the difference in the heat transfer to the evaporating refrigerants due to their physical parameters difference. The data obtained thus are arranged in series at a constant temperature of flowing around water and shown in Figures 7 and 8.

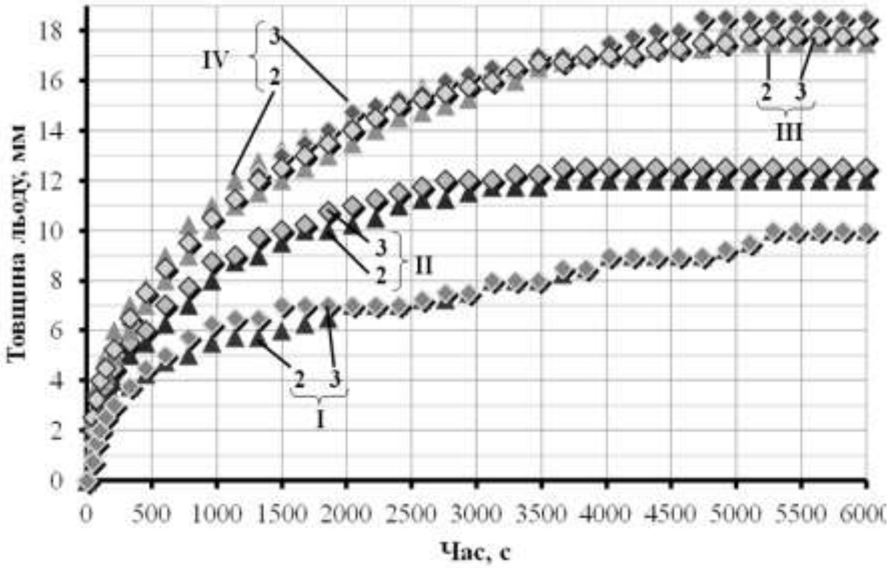


***Figure 7*** *–Ice thickness change with cooling by R12: 2, 3 – exp.sections number; I - $t_0$=-5 °C, $t_w$=+1,2 °C; II - $t_0$=-9 °C, $t_w$=+1,5 °C; III - $t_0$=-16 °C, $t_w$=+1 °C; IV - $t_0$=-20 °C, $t_w$=+1,5 °C.*

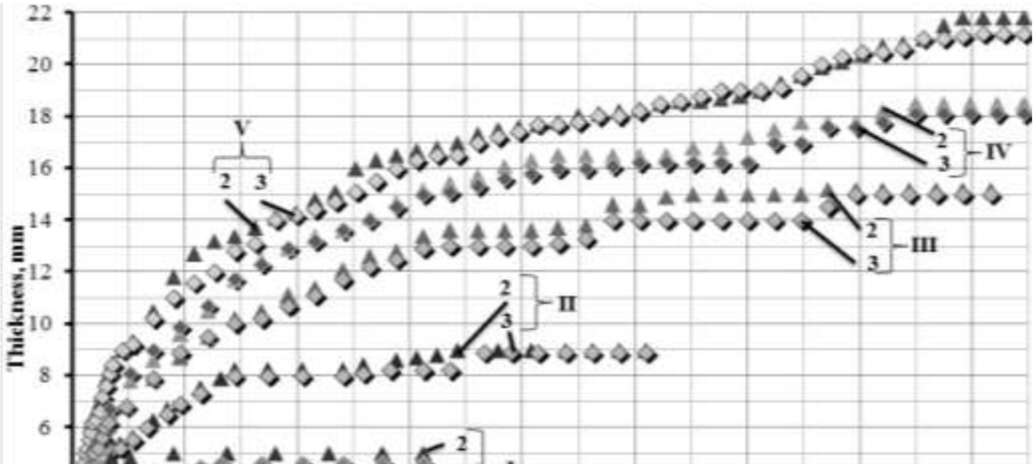


***Figure 8*** *– Ice thickness change with cooling by R22: 2, 3 – exp.sections number; I - $t_0$=-5 °C, $t_w$=+1,6 °C; II - $t_0$=-9,5 °C, $t_w$=+1,7 °C; III - $t_0$=-15 °C, $t_w$=+1,6 °C; IV - $t_0$=-20 °C, $t_w$=+1,6 °C; V - $t_0$=-25 °C, $t_w$=+1,6 °C.*

It is quite apparent that each series of data tends to reach a certain asymptotic value, which could be termed as a terminal for a given temperature difference value of ice thickness. Since a growing ice layer acts as a gradually increasing thermal insulation, the terminal value of ice thickness reflects a heat balance at which a state of thermal equilibrium is achieved. In this state only heat transferred from the overflowing water on the ice-water interface can be transferred to the refrigerant. No additional ice may be formed after the state of equilibrium has been achieved.

Similarly, the time intervals for reaching the terminal asymptotic values increase as the temperature difference increases. The asymptotic character of the experimental data allows choosing an optimal time interval of ice formation i.e. charging of a cold accumulator, since working after an asymptotic value of ice layer thickness has been reached leads to the direct loss of energy spent by the refrigeration compressors.

Right after the finishing of the experiments on ice formation, the experimentation on ice melting began. All the previous parameters were kept constant, but the flow of refrigerant through the cooled pipe stopped, thus the cooling ceased.

The experimental results with the melting ice were proceed as described above, grouped in sets according to the temperature of water and shown in Figure 9. Since the initial values if ice thickness reached in the previous experiments were different, the data are separated by the valued of the initial thickness. As it can be seen for Figure 9 all data are grouped along the lines with a certain slope. It is quite clear that the bigger the temperature of water is the steeper the line slope is, which is completely natural and is substantiated by the developed mathematical model.

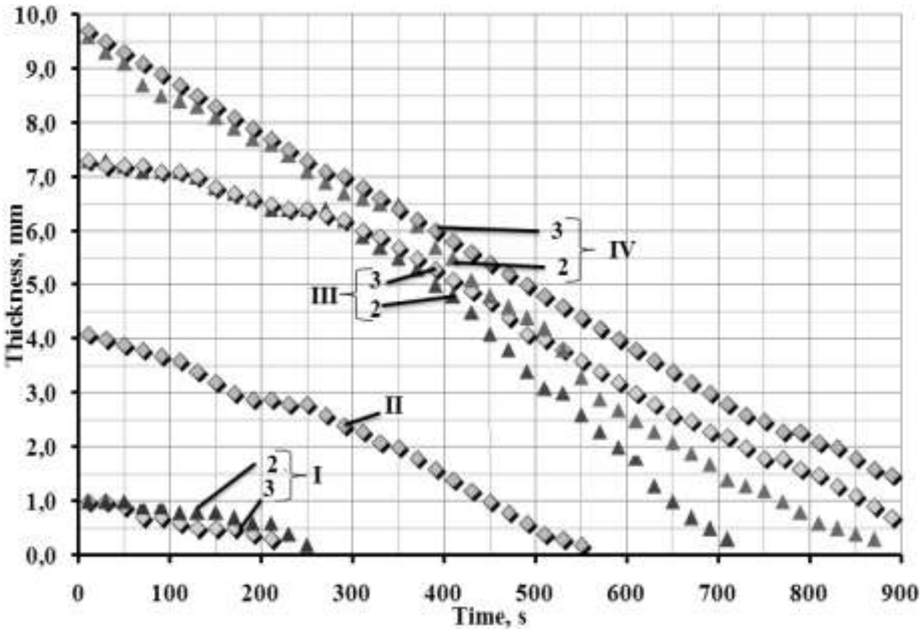


***Figure 9** – Ice thickness change in time at melting regime:*
*2, 3 – Experimental section number ; I - $t_w$=+4,3 °C;*
*II - $t_w$=+4,5 °C; III - $t_w$=+4,6 °C; IV - $t_w$=+5,4 °C.*

## IV. CONCLUSIONS

Experimental data obtained in the course of direct experimentation were obtained at the conditions of direct cooling heat transfer surface by the evaporating refrigerant.

Constantly growing ice layer thickness has been measured by optical registration and visual objects processing. The method has shown its accuracy repeatability and reliability.

The data on ice melting obtained by the same method were processed similarly and presented.

The data are being used for the derivation of semi empirical correlations for the calculation of engineering parameters necessary for ice accumulator designing calculations.

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# ДОСЛІДЖЕННЯ ПРОЦЕСІВ ГЕНЕРАЦІЇ І ПЛАВЛЕННЯ ВОДНОГО ЛЬОДУ НА ВЕРТИКАЛЬНИХ ОХОЛОДЖУВАНИХ ТРУБАХ

*Використання акумуляторів холоду є ефективним методом економії електроенергії, що базується на принципах генерації водного льоду на охолоджуваних вертикальних поверхнях в зонах нічного тарифу і таненні водного льоду, в зонах «пікових» годин. У короткі періоди пікового попиту значна кількість теплової енергії компенсується за рахунок плавлення льоду. Актуальним є не тільки визначення розміру акумуляторів холоду на основі балансових розрахунків, а критичним є визначення періоду накопичення водного льоду. Представлено експериментальну секцію для дослідження генерації водного льоду на вертикальній циліндричній поверхні, що охолоджується. Використано метод безперервної фіксації товщину льоду під час його плавлення. Експериментальні дані генерації і плавлення водного льоду представлено і проаналізовано. Отримані дані формують базис для виведення напівемпіричних кореляцій, що дозволять визначити часові інтервали, необхідні для генерації і плавлення заданої товщини водного льоду.*

***Ключові слова:*** *Лід; Диференціальне рівняння; Швидкість генерації льоду; Водний лід; Танення; Дослідна установка.*